

## TECHNOLOGY FOR AN INTELLIGENT, FREE-FLYING ROBOT FOR CREW AND EQUIPMENT RETRIEVAL IN SPACE

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### ABSTRACT

Crew rescue and equipment retrieval is a Space Station Freedom requirement. During Freedom's lifetime, there is a high probability that a number of objects will accidentally become separated. Members of the crew, replacement units, and key tools are examples. Retrieval of these objects within a short time is essential.

Systems engineering studies were conducted to identify system requirements and candidate approaches. One such approach, based on a voice-supervised, intelligent, free-flying robot was selected for further analysis. A ground-based technology demonstration, now in its second phase, was designed to provide an integrated robotic hardware and software testbed supporting design of a space-borne system.

The ground system, known as the EVA Retriever, is examining the problem of autonomously planning and executing a target rendezvous, grapple, and return to base while avoiding stationary and moving obstacles. The current prototype is an anthropomorphic manipulator unit with dexterous arms and hands attached to a robot body and latched in a manned maneuvering unit. A precision air-bearing floor is used to simulate space. Sensor data include two vision systems and force/proximity/tactile sensors on the hands and arms.

Planning for a shuttle flight experiment is underway. A set of scenarios and strawman requirements were defined to support conceptual development. Initial design activities are expected to begin in late 1989 with the flight occurring in 1994. The flight hardware and software will be based on lessons learned from both the ground prototype and computer simulations.

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### INTRODUCTION

A requirement exists to provide a retrieval capability for objects (astronauts, equipment, and tools) which have separated from Space Station Freedom. An analysis of the amount of crew Extra Vehicular Activity (EVA) likely during the lifetime the Space Station indicates, with high probability, that a number of objects will accidentally become untethered. Crew safety is top priority. In addition equipment may be too valuable to lose because it is required in operations and replacement is not available on the station. There is also collision potential on later orbits which, though small, has occurred previously.

The Space Station itself will lack the capability to chase separated crew or equipment and other vehicles such as the Space Shuttle orbiter or the Orbital Maneuvering Vehicle will not usually be available. Potential solutions based on manned, teleoperated, and autonomous capabilities have all been proposed.

Retrieval by a crew member using a Manned Maneuvering Unit (MMU) was examined in some detail. Analysis revealed that a short response time is critical. Many hours of real-time simulation of retrievals indicated that manned retrievals were unlikely to provide the required response time. In any case a major and unacceptable risk to the astronaut was involved.

The evolving requirements call for an unassisted deployment from a mounting on the external part of the airlock with propulsion capabilities provided by a more powerful version of the existing MMU. Performance guidelines include target retrieval within 120 minutes of subsystem deployment. Reliability considerations mandate the use of fault tolerant and fail-safe designs with embedded fault detection and isolation capabilities. Safety, reliability, robustness, and maintainability in space are key attributes.

Space Station Freedom advanced automation and robotics has been the subject of numerous symposia and papers [1, 2]. Appropriate roles for humans and machines in an evolving mix have been highlighted as a specific goal, with supervised intelligent system designs as ways to meet the needs of appropriate flexible-capability automation and robotics, thereby giving people-amplifier-type productivity gains.

The retrieval problem provides an opportunity to evaluate such systems in the form of a supervised, intelligent, free-flying space robot. The concept of supervised, intelligent, autonomous robotics provides for autonomous behavior of an intelligent type where human control is normally at a high level of goal-setting and involved in mixed initiative communication as a means of implementing decentralized, delegated management. By contrast, telerobotics provides a partially automated remote extension of human task performance with occasional control delegation for specific parts of tasks given to the telerobot for efficiency reasons.

Several previous efforts have laid a foundation for autonomous robot development including Shakey [3], JASON [4], the RPI Rover [5], the JPL Rover [6], and the Stanford Cart [7], among others. These first-generation autonomous robots were used to explore basic issues in vision, planning, and control. However, they were all seriously hampered by primitive sensing and computing hardware.

More recent efforts have overcome many of these limitations, and very sophisticated second generation autonomous robot testbeds have evolved. Some of these efforts include the developments of HILARE [8], the FMC Autonomous Vehicle [9], the Autonomous Land Vehicle (ALV) [10], the various CMU mobile robots [7], and the Ground Surveillance Robot (GSR) [11]. A more general and complete discussion of autonomous vehicle history and technical issues has been given by Harmon [12]. While operational versions don't exist, much advantage can be obtained from these efforts.

By comparison, the space retrieval task seems simpler in some respects. While automatic control, such as is available in automatic guided vehicles (AGV), remotely piloted vehicles (RPV), and missiles, is not adequate here due to the dynamic environment, the more general solutions to vision and planning in completely unknown environments are not required. There are few objects in space; these are cooperative, and largely knowable. In low earth orbit, space is characterized by high thermal gradients, radiation levels, high vacuum, microgravity and reaction-force aspects, and constrained and delayed access to information, resources, and equipment. Supervision by voice is a natural, flexible means of providing the primary human-machine interface (supplemented with helmet displays) required. This requires limited natural

language understanding integrated with the environment and task as well as functions like planning and reasoning. Complete intelligent autonomy of the R2D2/C3P0-type is not required nor achievable.

However, significant technology advances will be necessary before even this simple, crucial application can be practically addressed. These advances will only be gained by implementing autonomous robot simulations and testbeds so as to gain experience with the developing technology.

The potential evolution of such a robot to an EVA crew helper is obvious. Routine inspections, fetching tools, holding objects, could all improve EVA safety and productivity.

The EVA Retriever ground-based technology demonstration study [13, 14] was established to design, develop, and demonstrate in three phases an integrated robotic hardware/software system which supports design studies of a space borne crew rescue and equipment retrieval capability. Goals for each phase were established [15] in support of the overall goal of building and evaluating the capability to retrieve objects (astronauts, equipment, and tools) which have accidentally separated from their spacecraft. The Phase I goals were to design, build, and test a retriever system testbed by demonstrating supervised retrieval of a fixed target. Phase II goals are to initiate simulations and to enhance the testbed subsystems with significant intelligent capability by demonstrating target retrieval while avoiding fixed, arbitrarily oriented obstacles. Phase III goals are to more fully achieve supervised, intelligent, autonomous behavior by demonstrating retrieval of a moving target while avoiding moving obstacles.

Space Station scenarios [16] were examined in some detail to aid in the definition of a set of design reference missions. A number of systems engineering studies were conducted in support of the software design. Level A requirements for a projected Space Station version were developed in a conceptual design study [17]. Level B software requirements were derived in greater detail for this possible future Space Station application [18].

This paper gives an overview of the experimental hardware and software and a brief summary of the Phase II experiment. These are related to the current planning for a shuttle flight experiment.

## PHASE II PROTOTYPE

The technology demonstrations are being conducted on the JSC Precision Air Bearing Floor (PABF). The retriever/MMU unit is mounted on a test stand with

compressed air supplied thru an umbilical. The MMU has twenty-four thrusters, four on each rectangular side. The MMU accepts simple translation and rotation on/off commands to fire thrusters providing fixed acceleration in any of the three translational or three rotational directions.

The current prototype (Figure 1) is an anthropomorphic manipulator unit with dexterous arms and hands attached to a robot body and latched in an MMU. Sensor data include accelerometers, gyroscopes, two independent vision systems, and force/proximity sensors on the hands and arms. The primary vision system consists of a laser scanner imager and video camera mounted on a controllable turntable. The secondary vision system is a multicamera video tracking system, with a chest camera array and a camera in one of the hands.

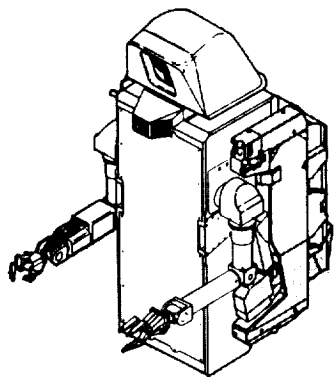


Figure 1. Retriever test article.

The prototype has dual 6-degree-of-freedom arms. The arms have roll and pitch at the shoulder, elbow, and wrist. One of the arms has a dexterous grasping hand and the other has a three fingered gripper. The dexterous hand incorporates proximity sensors in order to support adaptive grasping of an object by monitoring force and moment buildup.

The processor configuration contains seventeen transputers (five of which are dedicated to vision processing), several 68020 processors, a 80386 processor, and a special purpose video tracker subsystem.

The EVA Retriever software is required to autonomously plan and execute a target rendezvous, grapple, and return to base while avoiding stationary and moving obstacles. The system is required to monitor plan execution, estimate probability of mission success, and dynamically replan whenever needed to achieve system goals.

The software architecture (Figure 2) incorporates a hierarchical decomposition of the control system that is horizontally partitioned into five major functional subsystems: perception, world model, reasoning, sensing, and acting. The design utilizes hierarchical flow of command and status messages but allows horizontal flow of data between components at the same level. Computation is performed at the lowest possible level and, in general, knowledge-based systems are utilized only when algorithmic solutions are lacking in power or flexibility. This approach handles multiple levels of abstraction well and permits the incorporation of special data paths between time critical components.

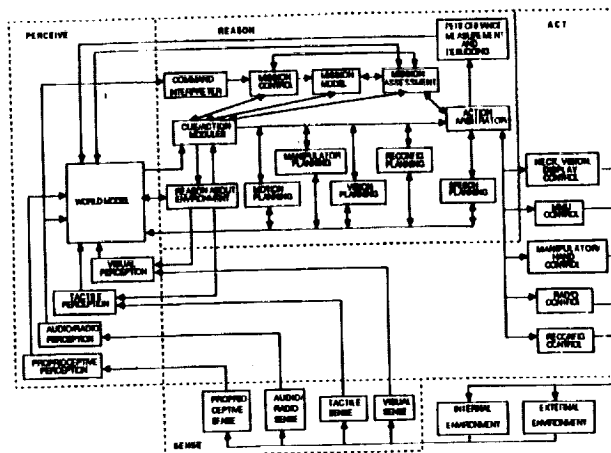


Figure 2. EVA Retriever software components.

The overall design provides for an evolutionary system improving in capability over time and as it earns crew trust through reliable operation. Additional details on the hardware and software design may be found in Erickson et. al. [14].

## PRELIMINARY PHASE II RESULTS

At the time of this writing, hardware and software integration is nearing completion in preparation for PABF evaluations and demonstrations in the summer of 1989. Nevertheless, some preliminary results are available. Several static tests have been successfully completed which indicate successful integration and operation of subsystems.

The computer simulation testing carried out in Phase II for purposes of unit and integrated software dynamic testing of prototype designs has already paid major dividends. First, we have gained solid confidence in the Retriever's behavior and the software which drives this behavior. Second, we have been able to investigate

detailed requirements issues and design issues into which we otherwise would have little means to gain insight. Third, as a result, we have been able to make numerous minor requirements, design, and implementation changes and test them before hardware integration or PABF evaluations. So, as expected, the simulation testing has been very useful and efficient even though it is not the whole answer. Building the complete artifact and testing it in a set of physical tests including grappling cannot be simulated and is required to gain confidence in the design and understand its limitations.

In attempting to design realtime visual perception for grasping some preliminary results were obtained which relate to sensors and engineering of computer hardware and software for robotic applications. Images of moving objects taken with the laser scanner at 0.8 seconds per frame show a warped and distorted image of the objects for even reasonably slow moving objects. This result indicates that frame rates need to be increased substantially to deal with moving objects.

The range image processing from laser scanners done by Vemuri and Aggarwal (19) using curvature representations in Constructive Solid Geometry (CSG) approaches for stationary objects establishes, in principle, an algorithm for constructing the surface of an arbitrary, 3-D unknown man-made object and, in particular, demonstrates the need for spline fitting, which is computationally intensive. Even though this algorithm is parallel in each "patch" of the image, extrapolation from the Vax sequential implementation to a parallel transputer one still leaves a computational period of many minutes which is not near enough to realtime to be a practical solution for robotic grasping. A simpler representation with less computational requirements seems indicated and is being sought without loss of generality. There are also sensor requirements implied by this algorithm which means many more pixels from the object are needed than our current scanner provides (that is, the IFOV must subtend a much smaller angle which coupled with higher frame rates may require greater laser power).

The performance measurement and debugging function is difficult conceptually because defining good measures of performance is not easy, but some progress has already been made. The motivation is simple -- with measurements of performance occurring constantly, the Retriever, its supervisor, and its designers can know how it is performing. As we are focused at the moment on requirements and design, measurements of performance provide the data needed to quantify limitations and thus where design improvements will be most useful. One measure of performance is the time required for rendezvous for a given arrangement of obstacles and target. Another is the thruster durations during this rendezvous needed for translations and rotations. A third is the distance travelled. In space,

minimum time and minimum fuel trajectories are of interest. On the PABF, "good" trajectories weigh distance, time, and fuel.

Preliminary measurements of time for rendezvous and total thruster durations for one distance and object/target scenario from testing against simulation gave about 130 seconds for rendezvous and 13 seconds total thruster duration for the case with translations and rotations (including the head) occurring in parallel. Measurements on the air bearing floor will be compared to these simulation results.

Debugging is another important operational function. Although we have used the best third-party debugging software we could find for a multi-processor transputer configuration, we do not yet have an adequate capability, meaning it takes too long to find bugs because the tools are not supportive enough.

Another result from simulation testing dealt with minor modifications to the design of the world model in reasoning about whether an object was an object seen before or a new object. This deals with robustness to inertial measurement drift in space when no spacecraft radar is available for tracking Retriever and multiple objects. The event can be described as an unsensed change of location of Retriever. On the PABF this can occur due to floor disturbances causing sliding not sensed by accelerometers or gyroscopes. We use vision derived object location to provide feedback to Retriever about Retriever location. However, when an object appears to be in a relative location where no object was seen the last look and far enough from where one was seen, we call it a new object. Our design is now more robust in this one respect due to simulation testing and subsequent design modifications.

Another testing/modification case of this same kind dealt with parallel actions, that's doing two or more things simultaneously rather than sequentially. In the situation where a new object is seen while on a planned rendezvous trajectory, motion continues until a new motion plan is computed, or if too close to impact, a hold is executed until a new plan is available. We expect reactive planning to further improve our responsiveness.

## DYNAMIC ENVIRONMENT

Phase III of the Ground Demonstration Program was intended to deal with moving objects in a dynamic environment (Phase II dealt with stationary objects). Consequently, requirements, design, implementation, and evaluation of techniques for moving objects have been planned for 1990.

An overview of our technical approach to moving objects is simply that Retriever needs to formulate and execute plans using visual perception for object search, acquisition, recognition, tracking, and grapple. Retriever will formulate and execute plans for mobility with moving obstacle avoidance to rendezvous with the moving target. Retriever will use dexterous manipulation and a grapple mechanism for grapple, tethering, and transfer. The plans need to be adaptable to the specific situation and to compensate for unknowns with reactive plans which can tolerate failed actions or react to unexpected events.

### Safety Policy in Software

A dynamic environment raises the issue of providing safety. Retriever must be safe to use as it carries out its retrieval tasks, which will vary, in the face of unintended contacts, failed actions (grapples), and mechanical failures. We mean by being safe that Retriever must not harm an astronaut, any part of another spacecraft, or itself. We will employ technology (to provide safety) which supports guarantees on robot behavior.

Our approach is to provide safety via two approaches. The first is software safety technology which is concerned with ensuring that software will execute in a systems context without resulting in states of unacceptable risk and will take actions to remove the Retriever from conditions of unacceptable risk if they should occur due to detectable hardware or software faults or command errors -- a policy that states that Retriever software will neither create nor ignore states of unacceptable risk. Risk is defined as danger times hazard severity where danger is the probability of a hazardous state leading to an accident and severity is the worst possible damage that could result. A hazards analysis for software is planned for 1990.

The second approach is to provide safety via reactivity where we will encode plans as networks of responses to possible situations and where guarantees on behavior are sought via a finite state machine analogy.

### SHUTTLE FLIGHT EXPERIMENT PLANNING

Planning for a Shuttle flight experiment in 1994 is underway. The primary technical objective of the flight experiment is to develop and demonstrate from the STS base a flight prototype of a crew supervised, intelligently autonomous space robot for the retrieval of free-floating objects. A tentative schedule of activities required is shown in Figure 3.

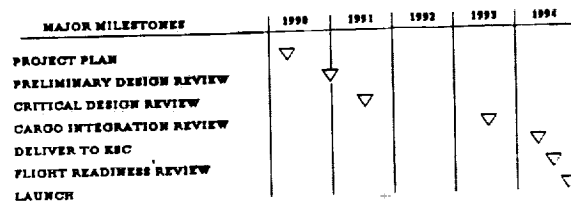


Figure 3. Preliminary Flight Experiment Schedule.

A preliminary set of scenarios were defined to support conceptual development. The primary demonstrations are the autonomous robotic retrieval of free floating targets in space (tool, astronaut model). The set of scenarios is organized in order from simple to more difficult to maximize success and minimize risks. There are essentially three groups of scenarios: those in the payload bay prior to commitment of EVA; those acquisition, tracking, and grapple tests in the payload bay with an EVA astronaut as supervisor; and free-floating target retrieval demonstrations well out of the Shuttle bay organized in order of increasing difficulty.

These latter demonstrations include a fixed target retrieval held by the Remote Manipulator System on an extension pole, a free-floating but stable tool retrieval, a rotating tool to be retrieved using a grapple mechanism (such as a net), a tool retrieval with obstacle avoidance (no obscuration of target), a tool retrieval with temporary obscuration of the target by an obstacle, and an astronaut model retrieval.

Initial requirements and design activities are planned to begin late in 1989 for the actual flight in 1994. The necessary evaluations of approaches to deal with moving objects in a dynamic environment must be factored into the design. In fact, flight hardware and software will be based on lessons learned from both the ground prototype and a complementary series of computer simulations of moving objects. Flight system reliability will be better understood, crew training will be easier, and Shuttle integration will be less costly due to the use of the previously flown MMU.

The Crew and Equipment Retrieval Systems (CERS) is an identified part of the Space Station. A CERS study is currently underway by the Space Station Work Package 2 contractor, McDonnell Douglas. The study is currently in Part I which is a requirements definition

phase. Part I products will include a description of concepts evaluated and their programmatic impacts, and recommendation for retrieval capability implementation for both Station PMC and for Station Phase II. The Part I study will also define a study plan for the Part II CERS study. The Part II study would be utilized to produce at least two point design concepts. One concept would possibly be a simple astronaut self-help device for use by a conscious crew member in the early Station operation. The second design concept produced would be a free-flying retrieval system capable of satisfying all appropriate crew/equipment retrieval requirements.

The CERS study is directed to consider a supervised intelligent autonomous system such as the EVA Retriever and its related test programs. The EVA Retriever flight experiment would thus serve as a test bed for a variety of functions and equipment directly applicable to the Space Station CERS. This includes tracking, control, target recognition, grapple methods, crew control, and Station interface definition.

## CONCLUSION

Evaluation of improved technology for the practical realization of a potential solution to the need for retrieval of crew and equipment in space near their spacecraft is underway. Preliminary results from the second phase of the ground testbed activity have been obtained from both computer simulations and the ground prototype. Important evaluations of technology to deal with a dynamic environment of moving objects including safety software are planned for 1990. Hardware and software lessons learned will be factored into planning for a Shuttle flight experiment. Assessment of practicality will rest on experimental evidence when these are completed.

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